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MODULAR DISPERSION COMPENSATOR

Field of the Invention

[0001] The present invention relates generally to WDM optical transmission systems, and more particularly to a method and apparatus for providing dispersion compensation in a WDM optical transmission system.

Background of the Invention

[0002] In recent years, Wavelength Division Multiplexed (WDM) and Dense Wavelength Division Multiplexed (DWDM) optical transmission systems have been increasingly deployed in optical networks. Although DWDM optical transmission systems have increased the speed and capacity of optical networks, the performance of such systems, especially those providing bit rates of 10 Gb/s or more, has traditionally been limited by various factors such as chromatic dispersion and the non-linearity in an optical fiber's refractive index, which can cause spectral broadening of optical pulses and degrade the transmission of high speed optical signals. Because such optical signal degradation tends to accumulate along transmission paths, chromatic dispersion and non-linearity can significantly limit the transmission distance of high speed optical signals.

[0003] Chromatic dispersion refers to the fact that different wavelengths of light pass through an optical fiber at different speeds, thereby causing a pulse of light propagating through the optical fiber to broaden. Chromatic dispersion is often characterized as first, second and third order dispersion. First order dispersion is the rate of change of the refractive index with respect to wavelength in the fiber. First order dispersion is also referred to as group velocity. Second order dispersion is the rate of change of the first order dispersion with respect to wavelength. Second order dispersion produces the pulse broadening. Third order dispersion is the rate of change of broadening with respect to a change in wavelength. This is often referred to as the dispersion slope.

[0004] Several solutions have been proposed to mitigate the effects of dispersion in transmission fibers. One technique involves the use of a compensating optical fiber having an appropriate length and which has a dispersion that is opposite to the dispersion characteristic of the transmission fiber. As a result, the dispersion in the transmission

fiber is substantially canceled by the total dispersion in the compensating fiber. Since dispersion is wavelength dependent, the amount of dispersion compensation that is needed differs from wavelength to wavelength. WDM and DWDM optical transmission systems therefore typically provide dispersion compensation to each wavelength individually. Since this solution can be difficult and expensive to implement, dispersion compensation is sometimes performed on groups of wavelengths so that each wavelength within a group receives the same amount of dispersion compensation.

[0005] FIG. 1 shows a known chromatic dispersion compensator 105 for performing dispersion compensation on groups of wavelengths. In operation, the dispersion compensator first splits the bandwidth of the optical spectrum into a series of bands, equalizes the dispersion of each band individually, and finally recombines the signals onto a common path for continued transmission. In FIG. 1, the signals reach the compensator on fiber path 201 and enter a 1xN optical splitter 203, which divides the power of the optical signal onto output paths 209_1, 209_2, 209_3, . . . 209_N. The signals propagating along the N output paths respectively enter optical band-pass filters 204_1, 204_2, 204_3, . . . 204_N with a center wavelength of λ_1, λ_2, λ_3, ...λ_N, respectively. The optical bandpass filters 204 separate the usable bandwidth into N distinct bands. The signals emerging from bandpass filters 204_1, 204_2, 204_3, . . . 204_N each enter a respective dispersion equalizing fiber 205_1, 205_2, 205_3, . . . 205_N and possibly loss elements 208_1, 208_2, 208_3, . . . 208_N. The signals are subsequently recombined in coupler 206 before exiting the dispersion compensator on fiber 207. The dispersion in each of the plurality of compensating fibers 205_1, 205_2, 205_3, . . . 205_N is selected so that the average chromatic dispersion of the concatenated transmission spans 104 upstream from the dispersion compensator 105 and the equalizing sections 202 and 205 are substantially returned to zero at each of the center wavelengths λ_N. Additional details concerning the dispersion compensator shown in FIG. 1 may be found in U.S. Patent No. 6,137,604.

[0006] One limitation of the aforementioned known dispersion compensator is that it is difficult to increase the number of wavelength bands as additional channels are added to increase system capacity sometime after the dispersion compensator is initially installed and operational. For example, the splitter 203 as initially deployed must include the maximum number of anticipated output paths 209 that eventually may be required. That is, if the dispersion compensator is initially required to provide only N bands, but if

it is used in a transmission system that is ultimately anticipated to provide N+x bands, the splitter 203 must be deployed with N+x output paths 209 even though x of them will initially go unused. Likewise, N+x equalizing fibers 208 need to be provided even though only N of them are initially required.

[0007] Another limitation of this approach is that each dispersion equalizing fiber 205_i must supply the total amount of compensation required by each band i, even though this amount is only incrementally different from that required by adjacent bands.

[0008] Accordingly, it would be desirable to provide a dispersion compensator in which modular functionality can be provided so that its capacity can be increased as needed in a relatively easy and inexpensive manner, and in which the amount of equalizing fiber required can be reduced.

Summary of the Invention

[0009] In accordance with the present invention, a dispersion compensator is provided that includes a first plurality of dispersion compensating modules. A first of the dispersion compensating modules includes a first input port for receiving a WDM optical signal having a prescribed bandwidth, a second input port, and first and second output ports. A dispersion compensating element is coupled to the first input port for substantially compensating each wavelength in the WDM optical signal for dispersion at a prescribed wavelength within a first sub-band of said prescribed bandwidth. A first wavelength selective arrangement is provided to (i) direct to the second output port wavelengths received from the dispersion compensating element outside the first sub-band and (ii) direct to the first output port wavelengths received from the second input port and wavelengths received from the dispersion compensating element within the first sub-band. A second of the dispersion compensating modules includes a third input port optically coupled to the second output port of the first dispersion compensating module for receiving the wavelengths of the WDM optical signal outside the first sub-band, a fourth input port, and third and fourth output ports. The third output port is coupled to the second input port of the first dispersion compensating module. A second dispersion compensating element is coupled to the third input port for substantially compensating each wavelength received from the third input port for dispersion at a prescribed wavelength within a second sub-band of the prescribed bandwidth. A second wavelength

selective arrangement (i) directs to the fourth output port wavelengths received from the second dispersion compensating element outside the second sub-band of said prescribed bandwidth and (ii) directs to the third output port wavelengths received from the fourth input port and wavelengths received from the second dispersion compensating element within the second sub-band.

[0010] In accordance with another aspect of the invention, the prescribed wavelength in the first sub-band for which dispersion is substantially compensated is a center wavelength of the first sub-band.

[0011] In accordance with another aspect of the invention, the prescribed wavelength in the second sub-band for which dispersion is substantially compensated is a center wavelength of the second sub-band.

[0012] In accordance with another aspect of the invention, the first wavelength selective arrangement includes a pair of filter elements each reflecting the wavelengths received from the first dispersion compensating element within the first sub-band and transmitting the wavelengths received from the first dispersion compensating element outside the first sub-band and the wavelengths received from the second input port.

[0013] In accordance with another aspect of the invention, the second wavelength selective arrangement includes a pair of filter elements each reflecting the wavelengths received from the second dispersion compensating element within the second sub-band and transmitting the wavelengths received from the second dispersion compensating element outside the second sub-band and the wavelengths received from the third input port.

[0014] In accordance with another aspect of the invention, the first plurality of dispersion compensating modules includes N dispersion compensating modules, where N is an integer equal to a number of wavelength bands into which the prescribed bandwidth is to be divided.

[0015] In accordance with another aspect of the invention, the dispersion compensating elements are single mode fibers.

[0016] In accordance with another aspect of the invention, the dispersion compensating elements are fiber diffraction gratings.

[0017] In accordance with another aspect of the invention, a gain or loss element is

coupled to the dispersion compensating element of least one of the first and second dispersion compensating modules.

[0018] In accordance with another aspect of the invention, a gain or loss element is coupled to the dispersion compensating element of each of the first and second dispersion compensating modules.

[0019] In accordance with another aspect of the invention, a common dispersion compensating element is provided for translating an average zero dispersion wavelength of the prescribed bandwidth to one end of the prescribed bandwidth. The common dispersion compensating element couples the first input port of the first dispersion compensating module to the dispersion compensating element of the first dispersion compensating module.

[0020] In accordance with another aspect of the invention, a method is provided to compensate for dispersion of a WDM optical signal. The method begins by directing a WDM optical signal having a prescribed bandwidth to a first dispersion compensating element and substantially compensating, with the first dispersion compensating element, each wavelength in the WDM optical signal for dispersion at a prescribed wavelength within a first sub-band of the prescribed bandwidth. The method continues by directing to a second dispersion compensating element wavelengths received from the first dispersion compensating element outside the first sub-band and substantially compensating, with the second dispersion compensating element, each wavelength received from the first dispersion compensating element for dispersion at a prescribed wavelength within a second sub-band of the prescribed bandwidth; The wavelengths received from the second dispersion compensating element are combined within the second sub-band of the prescribed bandwidth with the wavelengths received from the first dispersion compensating element within the first sub-band.

Brief Description of the Drawings

[0021] FIG. 1 shows a known chromatic dispersion compensator 105 for performing dispersion compensation on groups of wavelengths.

[0022] FIG. 2 shows the dispersion exhibited by a transmission path over the bandwidth λ_0-λ_n, which in this example is a linear function of wavelength.

[0023] FIG. 3 shows one embodiment of a modular dispersion compensator

constructed in accordance with the present invention.

Detailed Description

[0024] For purposes of illustration only and not as a limitation on the invention, the present invention will be described in terms of a transmission path that exhibits the dispersion shown in FIG. 2 over the bandwidth λ_0-λ_n. In this example the dispersion is a linear function of wavelength. Also, the average zero dispersion wavelength λ_0 of the transmission fiber is located at one end of the transmission band so that the dispersion compensation that must be provided to the individual channels is all of the same sign, either positive or negative. The bandwidth is divided into N bands to which dispersion compensation is to be provided. The dispersion compensation to be provided to each wavelength in a given band is an integral multiple of some fixed increment. For instance, if ΔD is the change in dispersion over the width of each band, then optimum compensation involves compensating each wavelength within the band with a value of -$\Delta D/2$ for band 1, -(3/2) ΔD for band 2, -(5/2) ΔD for band 3, and so on. In this way the dispersion at the center wavelength of each band is zeroed.

[0025] FIG. 3 shows one embodiment of a modular dispersion compensator 300 constructed in accordance with the present invention. The dispersion compensator 300 includes a concatenation of dispersion compensating modules 301_1, 301_2, ... 301_N. That is, the number of dispersion compensating modules 301 that are provided is equal to the number of wavelength bands to which dispersion compensation is to be provided. Each dispersion compensating module 301 is a four port device that includes an input port 302, a partially compensating output port 303, a return port 304, and a compensating output port 305.

[0026] With respect to any given module 301_i, the WDM signal to which dispersion compensation is to be provided is initially received by the module on input port 302_i and is directed to dispersion compensating element 308_i. Dispersion compensating element 308_i provides an amount of dispersion compensation required to impart the incremental increase in compensation that is required for band i. For example, assuming as in FIG. 2 that the change in dispersion over the width of each band is ΔD and that the dispersion at the center wavelength of each band is to be zeroed, the dispersion compensating element

308_1 in module 301_1 should provide a compensation of -ΔD/2. Likewise, the dispersion compensating elements 308_2-308_n each provide a compensation of –ΔD.

[0027] In the embodiment of the invention shown in FIG. 3 the dispersion compensating elements 308 are single-mode fibers. Of course, those of ordinary skill in the art will recognize that many other optical devices may be employed to provide the necessary dispersion compensation. For example, fiber diffraction gratings may be used instead of single-mode fibers.

[0028] After traversing dispersion compensating element 308_i, the WDM signal is directed to a first bandpass filter 310_i. First bandpass filter 310_i is configured to reflect the wavelengths in band i and transmit therethrough the wavelengths in the remaining bands (i+1) to N. The wavelengths reflected by the first bandpass filter 310_i are directed to a second bandpass filter 312_i that reflects these same wavelengths (i.e., the wavelengths in band i) to compensating output port 305. That is, the first and second bandpass filters 310_i and 312_i have the same transmission bands and the same reflection bands. The wavelengths transmitted through the first filter 310_i are directed to partially compensating output port 303_i.

[0029] The partially compensating output port 303_i of module 301_i is optically coupled to the input port $302_{(i+1)}$ of module $301_{(i+1)}$. In this way module $301_{(i+1)}$ receives the wavelengths in wavebands (i+1) to N so that a dispersion compensation of –ΔD is imparted to each wavelength by dispersion compensating element 308(i+1). The operation of module $301_{(i+1)}$ continues in a manner similar to that described above in connection with module 301_i. That is, first and second bandpass filters $310_{(i+1)}$ and $312_{(i+1)}$ reflect the wavelengths in band (i+1) to compensating output port $305_{(i+1)}$ and transmit to partially compensating output port $303_{(i+1)}$ the wavelengths in bands (i+2) to N. The second filter $310_{(i+1)}$ reflects the wavelengths in band (i+1) to compensating output port $305_{(i+1)}$, which in turn is optically coupled to the return port 304_i of module 301_i so that the wavelengths in band (i+1) are directed to compensating output 305_i via second bandpass filter 312_i.

[0030] In summary, dispersion compensating module 301_i imparts an increment of dispersion compensation that serves as the final increment required by the wavelengths in band i and as one part of the total dispersion compensation required by the wavelengths in bands (i+1) to N. The wavelengths in band i are therefore directed to compensating output

port 305_i so that they can be ultimately passed to the compensating output port 305_1 of module 301_1, where they exit the dispersion compensator 300. The wavelengths in bands (i+1) are directed to partially compensating output port 303_i so that they can be received by successive modules for receiving additional dispersion compensation.

[0031] One important advantage of the present invention is that individual modules 301 can be added to the dispersion compensator 300 as they are needed. For example, if only the wavelengths in band 1 are initially being used, then only module 301_1 needs to be installed. As successive bands are populated, the corresponding modules 301_2, 301_3 ... 301_N can be added to the dispersion compensator 300. Another important advantage is that because the modules are cascaded so that any given dispersion compensating module imparts dispersion compensation to all wavelengths that traverse subsequent or downstream modules, the total amount of dispersion compensating fiber that is required is substantially reduced in comparison to the dispersion compensator shown in FIG. 1.

[0032] In some embodiments of the invention the individual dispersion compensating modules 301_i may each include a loss or gain element (not shown) to facilitate gain equalization within the bands. For example, the loss or gain elements may be used to equalize the received signal-to-noise ratio of the wavelengths.

[0033] In some cases the wavelengths may be so closely spaced (e.g., 50 GHz or less) that bandpass filters that can satisfactorily separate adjacent wavelengths may be difficult to obtain. In this case the modular dispersion compensator may be preceded by a deinterleaver that separates the even and odd wavelengths onto different output paths, effectively doubling the channel spacing on the each output path. In this arrangement two of the modulator dispersion compensators 300 are employed, each receiving the wavelengths from one of the output paths of the deinterleaver. The dispersion compensated output signals from the two modulator dispersion compensators are then directed to the inputs of an interleaver so that the even and odd wavelengths are recombined.

[0034] If the average zero dispersion wavelength λ_0 of the transmission fiber is located within the transmission band instead of at the end as in FIG. 1, a common dispersion compensating element may be located prior to the first dispersion compensating module 301_1. In way all the wavelengths will experience the dispersion compensation that is imparted by the common dispersion compensating element. The

dispersion of the common dispersion compensating element has the correct sign and magnitude to move the average zero dispersion wavelength λ_0 to one end of the transmission band so that the dispersion compensation that must be provided to each wavelength is all of the same sign. In some cases the common dispersion compensating element may be located in the first dispersion compensating module 301_1.

[0035] Alternatively, instead of a common dispersion compensating element two modular dispersion compensators may be provided, each of which provides dispersion compensation of the opposite sign. In this case a wavelength dependent optical splitter is employed, which splits the transmission band into two parts, each of which require dispersion compensation of the opposite sign. The outputs from the wavelength dependent splitter direct each part of the transmission band to the input of the appropriate modular dispersion compensator.